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CAPTURE RATE AS A FUNCTION OF SCHOOL SIZE IN OFFSHORE SPOTTED DOLPHINS IN THE EASTERN TROPICAL PACIFIC OCEAN

By

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Abstract

The frequency with which northeastern offshore spotted dolphins (*Stenella attenuata*) experience chase and capture by tuna purse-seiners in the eastern topical Pacific Ocean (ETP) was estimated by comparing dolphin school size frequencies in <u>sighting</u> data, taken from research vessel observer records, with dolphin school size frequencies in <u>set</u> data, taken from tuna vessel observer records. The objective of the study was to provide a preliminary basis for estimating stock-wide effects of (yet-to-be-measured) fishery-induced stress in these dolphins.

Our analyses indicate two major characteristics about the relationship between school size and the frequency with which dolphins in this stock experience chase and capture by tuna purse-seiners: first, that capture frequency increases rapidly with increasing school size, and second, that approximately half of the stock at any given time occurs in schools smaller than those apparently preferred by purse-seiners. Our results imply that if individual dolphins have a preference for associating with schools of a particular size, then individuals who associate primarily with large schools would be subjected to chase and capture much more often than those who associate with small schools. However, because the largest schools are relatively rare and account for a small proportion of individuals, the majority of dolphins in the stock experience would relatively few captures per year, although some would experience a very high rate. It is not known whether dolphins do indeed exhibit such a preference, or if instead individuals associate with schools from a wide range of sizes at different times.

Our estimate of the capture frequency for schools of size 1000 is 36.1 sets per year, or one set every 10 days, compared to well under once a year for schools of 100 animals. Our estimate of capture frequency for the median school size set on (560 animals) was 10.1 sets per year, or just under once per month.

Schools of 1000 or more dolphins are estimated to include less than one tenth of the total stock of northeastern offshore spotted dolphins, and are estimated to be set on approximately once a week each on average. Schools set on most often by tuna purse-seiners, containing from about 250 to 500 dolphins, comprise less than an estimated one third of the stock and are estimated to be set on between 2 and 8 times each per year on average. An estimated one half of northeastern offshore spotted dolphins occur in schools smaller than 250 animals; schools of this size are estimated to be set on less than twice per year each.

1. Introduction

Tuna fishermen in the eastern tropical Pacific Ocean (ETP) commonly catch large yellowfin tuna by first visually locating a school of dolphins and then surrounding it with a large purse-seine net in order to capture large yellowfin tuna (*Thunnus albacares*) that are often closely associated with dolphin schools in the ETP. The dolphins are released from the net, and the tuna are loaded aboard (NRC, 1992). This method, known as “fishing on dolphin”, has historically been a significant cause of dolphin mortality (NRC, 1992) but has also recently been suggested as a significant cause of fishery-related physiological stress in the dolphins involved, perhaps to the point of causing unobserved mortality or changes in reproductive success (e.g., Myrick and Perkins, 1995).

While it has not been possible to measure physiological stress directly in these dolphins, it is possible to use existing data to estimate how often an animal may experience chase and capture. While not a direct measure of stress, capture frequency provides at least a rough measure of the amount of fishery-induced disturbance that the dolphins affected by the ETP tuna fishery are experiencing. In this report, we describe methods developed to estimate capture frequency and discuss the implications of the estimates for fishery-related stress in the animals. We concentrate on the northeastern offshore stock of the spotted dolphin (*Stenella attenuata*) (Dizon et al., 1992; Figure 1), the dolphin species most commonly associated with tuna and historically most often used in fishing on dolphin (greater than 70% of dolphin sets annually for about the last 30 years (e.g., IATTC, 1990)).

A simple calculation (see Section 4.3) leads to a rough estimate for the mean number of times an individual dolphin is set on per year of (# dolphins set on) / (# dolphins) ≈ 8 times per year. However, simply knowing the overall average rate of capture is not sufficient to evaluate the potential stress effects on individuals because the rate for different animals may vary widely, depending on a number of factors including school size, geographic location, time of year, and the amount of associated tuna. In this paper, we investigate the effects of one of these interdependent factors. Specifically, we show that large dolphin schools (more than several hundred animals) are much more likely to be captured than are small schools (less than a hundred animals) because of a strong tendency for ETP purse-seine fishermen to concentrate their effort on larger schools, which tend to carry more tuna, and to virtually ignore smaller ones. However, this result does not directly give the capture rate for an individual dolphin, because animals may associate with schools of different sizes at different times.

To infer capture rates for individual animals, one must make assumptions about the dynamics of dolphin school size and membership. At one extreme, if school membership is completely fluid and individuals have no preference for schools of a particular size, all individuals will experience the same amount of interference in the long run (other factors being equal). At the other extreme, if school membership is completely static and dolphins always remain with the same school, dolphins in small schools can be expected to experience little interference from the fishery, while those in large schools can be expected to experience much more interference. The true situation for a given animal depends on the range of school sizes with which that animal associates, however, little is known about the fidelity of individual dolphins to specific schools or to schools of a particular size. In the absence of such knowledge, our main result in this report can be used to relate a preference for a characteristic school size to a rate of capture in the purse-seine fishery. While more specific information about an individual dolphin's rate of capture is obviously desirable, the results presented here provide a preliminary basis on which to assess the frequency of fishery-induced stress in northeastern offshore spotted dolphins.

In this analysis, we attempt to quantify the tendency for purse-seiners to set on large schools by comparing the relative frequency with which different sizes of schools are selected by fishermen for encirclement with the relative frequency with which schools of various sizes occur naturally. First, we estimate the probability distribution of sizes for dolphin schools within the geographic boundaries of the northeastern offshore stock (Figure 1), using observations from research vessels. This distribution models the relative number of schools of each size in the study area. Then we fit a smooth probability distribution to dolphin school sizes from tuna vessel sets. This distribution models the relative number of times schools of each size were set on. Finally, we use the ratio of the two estimated density functions, suitably scaled, to estimate the average number of times per year a dolphin school of a given size was set on. This estimated effect includes not only the tendency of fishermen to preferentially set on larger schools, but also any tendency to search in areas where large schools may be more prevalent. We do not investigate factors other than school size which affect a dolphin's rate of capture, such as the amount of tuna associated with a school.

The next section of this report summarizes the research vessel sighting data, the tuna vessel set data, and data collection methods. The third section details the statistical methods we used for estimation. The fourth section describes our results for the northeastern offshore stock. Finally, the last section discusses our assumptions and conclusions for the analysis.

2. Data

2.1 Research vessel sighting data

In 1986, the U.S. National Marine Fisheries Service (NMFS) initiated a multi-year research program to monitor trends in the abundance of dolphin populations in the eastern tropical Pacific Ocean (ETP). The program used National Oceanic and Atmospheric Administration (NOAA) research vessels to survey the ETP for several months out of each year and record sightings of all cetaceans encountered (Wade and Gerrodette, 1993). Research vessel observers recorded, among other data, estimates of the size and species composition of each school that was sighted.

The research vessel data used in this study consisted of dolphin school sightings from the 1986-90 and 1992-93 marine mammal surveys (Table 1, page 3). These seven surveys each occurred between late July and early December, and were carried out with teams of trained shipboard observers using 25x binoculars. We refer to the period between 28 July and 10 December as the "study period". The survey methods were designed to be as similar as possible across years. For detailed descriptions of the survey design, materials, and methods, see Holt et al. (1987), Hill et al. (1991), and Mangels and Gerrodette (1994).

Table 1. Summary of research vessel data by year and stratum. Search effort is defined as the distance travelled along the trackline with observers actively searching, with a sea state of Beaufort 5 or less. Sighting rate is defined as the number of northeastern offshore spotted dolphin schools sighted on-effort, within 5.5km of the ship's trackline, per 1000km of search effort. Middle and inshore strata as defined in Figure 1.

	Inshore stratum		Middle stratum	
Year	**Search effort (km)**	**Sighting rate**	**Search effort (km)**	**Sighting rate**
1986	9259.6	6.26	3456.8	4.92
1987	8522.8	7.27	4322.1	5.09
1988	6302.6	6.98	3371.3	3.26
1989	8375.1	9.67	3995.9	4.00
1990	7035.8	8.10	4744.1	3.79
1992	10189.0	5.99	0.0	—
1993	7952.7	6.29	584.4	3.42

During the first five surveys, the vessels traversed predetermined tracklines, where the placement was random within the constraints of even coverage within geographic strata and of vessel logistics. Search effort spanned the entire ETP, with 44% of the 135,300km of total search effort[1] within the stock boundaries of the northeastern offshore spotted dolphin. In designing these surveys, Holt et al. (1987) partitioned the ETP into several strata, based primarily on spotted dolphin density as observed from tuna vessels during the years prior to the surveys. Their survey design allocated search effort to each stratum based on these rough estimates of relative density, such that strata with greater apparent dolphin density received greater effort per unit area.

In the last two surveys, the vessels traversed systematically placed tracklines, where placement was random with respect to the dolphin populations. Search effort was primarily directed towards coastal ETP regions and approximately 55% of the 34,080km of total search effort was within the stock boundaries of the northeastern offshore spotted dolphin.

We used only those legs of search effort that were within the northeastern offshore stock boundaries (Figure 1), for which observers were actively searching ("on-effort"), and for which Beaufort sea state was 5 or below. We excluded sightings further than 5.5km from the trackline because school size estimates were generally unreliable for such distant schools. We used sightings of schools that included offshore spotted dolphins, plus a small number of schools recorded as "unidentified spotted dolphin". These latter schools were assumed to be primarily from the

1) Defined as total distance traversed with observers actively searching and sea state of Beaufort 5 or less.

offshore stock rather than from the coastal stock. We used a total of 499 research vessel sightings in this study.

For each dolphin school sighting, observers recorded, among other data, an estimate of the school's radial distance and relative bearing from the ship, which were transformed into an estimated perpendicular distance from the ship's trackline. Schools closer than 5.5km from the trackline were routinely approached to confirm species identification and to make estimates of school size. Typically, three observers estimated school size independently for each sighting. There were 16 sightings for which the observers were not able to make reliable estimates of school size, but, based on estimates of minimum school size, these did not appear to be biased in terms of school size or perpendicular distance with respect to the full data set. Therefore, we excluded those 16 sightings from our line transect estimates of effective search width and our estimates of school size distribution, but included them in the sighting counts used to scale our estimates of capture frequency (see Methods).

Dolphin school sightings are made from visual clues such as surface disturbances or associated bird flocks. Larger schools in general provide a more visible target, thus, large schools are more likely to be seen at long distances than are small schools. Therefore, the research vessel sighting data had a "size selection bias" towards larger schools because those were more likely to be seen on average. Our statistical model included a correction for that bias, as described in Methods. We did not correct for any "estimation bias" in research vessel observer estimates of school size, because it was not possible to make a corresponding correction for tuna vessel observer data (see Section 5.2).

2.2 Tuna vessel set data

Since the late 1970's, the Inter-American Tropical Tuna Commission (IATTC) and NMFS have placed trained observers aboard a significant percentage of ETP tuna purse-seiner vessels larger than 400 tons capacity. These observers collect data on the dolphins with which commercial species of tuna in the ETP commonly associate and monitor dolphin mortality due to purse seine fishing operations.

Detailed observer data were available from sets made by U.S. vessels. From these data, we used observer estimates of school size and species composition from spotted dolphin schools that were set on by tuna vessels within the northeastern offshore stock boundaries (Figure 1). Data from individual sets made by non-U.S. vessels were not available; however, count data summarizing observed numbers of sets and trips made by both U.S. and non-U.S. vessels were available.

During 1986, 1987, and 1988, a systematic sampling plan was used to place an observer aboard at least some trips for every U.S. fishing vessel. During these years, observer coverage on U.S. vessels averaged 65% for trips that involved sets on dolphins. Beginning in 1989, U.S. regulations required an observer aboard every trip made by a U.S. vessel. Only a very small number of trips did not carry observers, thus the data include essentially all dolphin sets made from 1989 onward by the U.S. fleet. Observer coverage on international (non-U.S.) vessels between 1986 and 1990 averaged 34% for trips that involved sets on dolphins (Table 2). In all cases, a single observer was placed aboard a selected vessel. We assumed that there was no sampling bias or "observer effect" on a captain's choice of schools to be set on. If the presence of an observer did affect which schools were set on with respect to school size, then our estimates of capture frequency were not based on "normal" fishing behavior. However, given the high observer coverage, carrying an observer is actually the more common situation for the U.S. fleet.

Table 2. Summary of tuna vessel data by fleet, year, and stratum. Coverage is defined as the percentage of fishing trips, involving sets on dolphins by vessels over 400 tons, that carried a scientific observer. Coverages and annual numbers of trips are taken from IATTC Annual Reports (e.g., IATTC 1992). Observed sets per trip is defined as the mean number of observed sets on northeastern offshore spotted dolphin schools for trips that involved sets on dolphins. Middle and inshore strata as defined in Figure 1.

			Observed sets per trip, 28 Jul - 10 Dec ("study period")			Observed sets per trip, annual		
Fleet	**Year**	**Coverage**	**Trips**	**Inshore**	**Middle**	**Trips**	**Inshore**	**Middle**
U.S.	**1986**	41.7	25	9.60	1.96	43	14.4	4.53
	1987	91.5	62	17.1	5.16	119	21.9	6.89
	1988	57.6	33	13.7	4.88	76	13.0	4.86
	1989	99.1	50	14.9	3.66	115	15.3	3.77
	1990	100.0	15	15.2	3.00	73	12.3	3.62
	Total	76.9	183	14.9	4.14	426	16.2	4.88
Intl.	**1986**	25.3	29	12.3	2.90	68	14.9	2.84
	1987	28.3	44	15.8	0.409	82	17.9	0.988
	1988	35.8	54	8.70	3.52	111	10.3	3.87
	1989	37.0	57	13.6	2.61	141	13.3	2.41
	1990	42.0	66	8.35	6.92	147	12.3	4.77
	Total	34.3	250	11.4	3.60	549	13.3	3.18

For school size and species composition estimates, we included only those sets that occurred during the study period (the time of year corresponding to the NMFS marine mammal surveys) for the years 1986-90. We used the observer's final "best" estimates, which were made after the conclusion of a set and which included all relevant information the observer had about the school, including counts of animals that evaded or were cut out of net encirclement[1] (IATTC, 1991;

1) Using this pre-encirclement school size means that while we are estimating the rate at which schools of a given size were set on, some dolphins involved in a given set were chased by the tuna vessel and its speedboats but not actually encircled by the purse-seine net. For the purposes of estimating numbers of sets as a measure of potential stress, we do not distinguish chase from capture.

NMFS, 1992). Note that these tuna vessel data only included schools that were actually set on, and not observations of schools that were sighted but not set on. We excluded 25 observations for which the observer was not able to make a reliable estimate of school size. A total of 3454 set observations were included in this study (Table 2, page 5). For a more detailed description of the observation programs, see IATTC (1989, 1992) or Jackson (1993).

From data collected by the scientific observers, we used the numbers of sets observed each year on the target stock, by both U.S. and non-U.S. vessels, during the study period and for the entire year (Table 2, page 5). Additionally, the total annual number of fishing trips that involved sets on dolphins has been estimated each year from tuna vessel logbook data (e.g., IATTC, 1992). Dividing the annual number of observed trips by the annual total number of trips gives the annual trip sampling fraction ("coverage"), which we took as known exactly. We further assumed that observer coverage was constant throughout the year, and thus that the sampling fractions were applicable for the study period as well as the entire year.

Anecdotal reports consistently imply that tuna vessels do not search for or set on dolphin schools at random when fishing on dolphin in the ETP. Since larger dolphin schools are observed to carry more tuna, they are presumably preferentially sought out and set upon. Therefore, the tuna vessel set data would have a strong selection bias towards large schools because those were more likely to be set upon, on average. It was this size selection bias that we attempted to quantify in this analysis. There was also the possibility of estimation bias in tuna vessel observer estimates of school size, which we did not correct for (but see Section 5.2).

2.3 Comparison of research vessel sighting data and tuna vessel set data

The research vessel sighting data represent search effort at a constant speed of 10 knots by two vessels for between three and four months annually over seven years. These vessels used two or three ship-based observers with binoculars to locate dolphin schools, and all dolphin sightings were recorded. The median estimated school size was 106. 48% of the estimates were less than 100, while only 1% were greater than or equal to 1000 (Figure 2a). Note that these quantiles as well as the estimated density in Figure 2a have not been corrected for size selection bias. The true distribution of school sizes was estimated to include a larger proportion of small schools (see Section 3.1 and Section 4.2).

The tuna vessel set data represent about 77% of the search effort during the same time period for the U.S. purse seine fleet, which ranged from 29 to 40 vessels during the years 1986-90. To increase their search efficiency, tuna vessels often travel at 15 knots, and crews use helicopters and communicate in "code groups" (Orbach, 1977) in addition to searching with binoculars from the ship. Not all schools that are sighted are set upon, and thus the observed sets represent a much larger effective sample size in terms of sightings, with the "missing" schools tending to be small. The median estimated school size was 560. Only 4% of the estimates were less than 100, while 26% were greater than or equal to 1000 (Figure 2b).

3. Methods

3.1 Statistical model

We modelled the true population of northeastern offshore spotted dolphin school sizes within the stock boundaries as an independent identically distributed (i.i.d.) sample of unknown size from a hypothetical infinite superpopulation of schools having a smooth probability density for their school sizes. To characterize the true population of school sizes, both the total number of schools, $N_{schools}$, and the probability density from which their school sizes were drawn, $\pi(s)$, needed to be estimated. While school size is really a discrete quantity, we approximated it using a continuous-valued random variate. Because the schools of interest in this study consisted of hundreds of animals, this approximation has no practical impact.

Because the sighting probability for schools at a given range depends on school size, there was a selection bias (relative to $\pi(s)$) towards larger schools in the research vessel observations. Thus, we modelled them as a biased sample of size $n_{schools}$ from the true population. Because the ships' tracklines were random with respect to the dolphin population, we assumed that there were no other selection biases. We denote the probability density of observed school sizes by $\pi^*(s)$ to distinguish it from $\pi(s)$, and note that

$$\pi(s) = \frac{w_{eff}}{w_{eff}(s)}\pi^*(s),$$

where $w_{eff}(s)$ is the effective line transect strip halfwidth for schools of size s and w_{eff} is the size-averaged effective strip halfwidth (Burnham et al., 1980, Appendix D). Both $w_{eff}(s)$ and w_{eff} depend upon the data truncation distance (Burnham et al., 1980), denoted by w and equal to 5.5km in this analysis. $\pi^*(s)$ was estimated from the observed school sizes. However, to estimate $\pi(s)$, we also needed to estimate $w_{eff}(s)$, as described below.

We modelled the schools associated with purse seine sets (both observed and unobserved) as a biased sample (with replacement) of unknown size from the true population of schools. To characterize these schools, both the total number of sets, N_{sets}, and the effective probability density from which their sizes were drawn, $p(s)$, needed to be estimated. $p(s)$ represents the superposition of the tuna fishermen's school size selection preference upon $\pi(s)$. Sizes were recorded for all sets on trips carrying observers, and so there was no additional observer selection bias (relative to $p(s)$). With the assumption of a random selection of trips, we treated the observed sets as an unbiased subsample of size n_{sets}, and estimated $p(s)$ directly from the observed sizes. There was some concern with serial correlation between sets, see Section 3.3.

3.2 Estimation

(a) <u>U.S. vessels, study period.</u>

Observer calibration experiments (Gerrodette and Perrin, 1991) indicated that research vessel observer estimates of school size, given the true size, were approximately normal on the log scale, with constant variance. This is consistent with a lognormal multiplicative error model. We combined research vessel observer estimates for each sighting using the corresponding MLE for the school size, i.e., a scale adjustment to the geometric mean. Under the assumption of unbiased estimation, our estimate of the i^{th} school size was

$$\hat{s}_i = \tilde{s}_i e^{\hat{\tau}^2/2}$$

$$\text{where } \tilde{s}_i = \exp\left(\sum_j \ln(s_{ij})/k_i\right), \quad \hat{\tau}^2 = \frac{\sum_{i,j} (\ln(s_{ij}) - \ln(\tilde{s}_i))^2}{\left(\sum_i k_i\right) - n_{schools}}$$

and where s_{ij} is the j^{th} observer's estimate of the i^{th} school, and k_i is the number of observers who made estimates of the i^{th} school. We use the term "adjusted mean" for $\hat{s}_i$ to distinguish this quantity from either the geometric mean, $\tilde{s}_i$, or the arithmetic mean. See Section 5.2 for more discussion of this estimator and the assumed error distribution. There was only a single tuna vessel observer for each set, and so we simply used the individual school size estimates from the tuna vessel set data.

The observed school size distributions from both the research vessel sighting data and from the tuna vessel set data were roughly lognormal in shape (Figure 2). We estimated $\pi^*(s)$ and $p(s)$ using an adaptive kernel density estimator on the logs of the observed school sizes, and then transformed back to the original scale (Silverman, 1986). We treated the observer estimates (adjusted mean estimates in the case of research vessel data) as exact measurements, and did not attempt to correct for the possibility of size estimation biases in either data set (see Section 5.2) or use a deconvolution kernel to account for estimation variance.

Our estimates of $w_{eff}(s)$ were based on modelling the inherent selection bias in the research vessel sighting data. We used a bivariate hazard-rate detection function in a size-dependent line transect analysis of the perpendicular sighting distances and sizes of the observed schools (Drummer and McDonald, 1987; Palka, 1993). Perpendicular distances were binned to reduce the effect of rounding in the data. School sizes were not binned, because we did not use a parametric model for their distribution.

We define the average capture frequency for a school of size s as

$$N_{capture}(s) = \frac{N_{sets}(s)}{N_{schools}(s)} = \frac{N_{sets}p(s)}{N_{schools}\pi(s)}.$$

Note that this definition implicitly assumes spatial homogeneity (but see Section 5.3). Setting the observed counts $n_{schools}$ and n_{sets} equal to their expectation gives

$$n_{schools} \approx \mathrm{E}[n_{schools}] = \left(\frac{2Lw_{eff}}{A}\right)N_{schools} \text{ and}$$

$$n_{sets} \approx \mathrm{E}[n_{sets}] = f_{trips}N_{sets},$$

where L is the total distance searched by the research vessels, A is the total area within the stock boundaries, and f_{trips} is the fraction of tuna vessel trips which carried an observer. Using the relationship between $\pi(s)$ and $\pi^*(s)$, and these moment equations for $n_{schools}$ and n_{sets}, we estimated the capture frequency for a school of size s as

$$\hat{N}_{capture}(s) = \frac{n_{sets}}{f_{trips}} \frac{2L\hat{w}_{eff}(s)}{An_{schools}} \frac{\hat{p}(s)}{\hat{\pi}^*(s)}.$$

Note that the factor w_{eff} cancels out and only $w_{eff}(s)$ remains. Without regard to the total number of sets or schools, the <u>relative</u> capture frequency as a function of school size may be estimated as $\hat{F}_{capture}(s) = \hat{w}_{eff}(s)\hat{p}(s) / \hat{\pi}^*(s)$.

Because there were so few schools smaller than 100 animals set on by tuna vessels, and so few schools larger than 1000 animals sighted from research vessels, we restricted our analysis to schools from 100 to 1000 animals, and computed estimates of capture frequency at intervals of 100 animals.

(b) <u>Stratification and pooling</u>

There were enough school size data from tuna vessel sets (n_{sets} = 3454) to reasonably stratify by location in our estimates of $p(s)$. We used essentially the same strata as those used by Holt et al. (1987), intersected with the stock boundaries (Figure 1). However, there were far fewer data from research vessel sightings ($n_{schools}$ = 499). Because of the uneven spatial distribution of sightings and the difficulty of making nonparametric estimates of a skewed density, we felt there were not enough sighting data to stratify in our estimates of $\pi^*(s)$. Likewise, we did not stratify in the bivariate hazard-rate model to estimate $w_{eff}(s)$.

Because the research vessel search effort and tuna vessel fishing effort were not evenly distributed over the range of the northeastern offshore stock, we stratified the counts n_{sets} and $n_{schools}$ geographically, using the strata defined in Figure 1.

We did not stratify by year in any of our estimates. For the research vessel data, we treated all seven cruises as independent random (with respect to the dolphin population) samples, and combined sighting counts and search effort (see Section 5.6) to make a single estimate of the average $N_{schools}$ over all years. Similarly, for the tuna vessel data, we combined observed set counts and computed overall trip sampling fractions to make a single estimate of the average N_{sets} over all years. School size data were also pooled over years to make estimates of both $\pi(s)$ and $p(s)$.

(c) <u>Extrapolation to the international fleet and to annual estimates</u>

Data from individual sets came only from U.S. tuna vessels, so that estimating capture frequency due to the entire fleet required some extrapolation. We made the assumption that a vessel's preference for school sizes upon which to make sets did not vary with country of origin, and thus extrapolated our estimate of $p(s)$ to the entire fleet. On the other hand, vessels from different countries are known to concentrate fishing effort towards different areas and set types[1], and we did not assume that patterns of effort remained the same across flags. Rather, our estimates of

1) Personal communication, Martin Hall, Inter-American Tropical Tuna Commission, La Jolla, CA.

total numbers of target sets by stratum were based on separate observed counts and sampling fractions for the U.S. and the international fleets,

$$\hat{N}_{sets} \;=\; \hat{N}_{sets}^{(US)} + \hat{N}_{sets}^{(Intl)} \;=\; \frac{n_{sets}^{(US)}}{f_{trips}^{(US)}} + \frac{n_{sets}^{(Intl)}}{f_{trips}^{(Intl)}} \,,$$

where geographic stratification and averaging over years have been suppressed for clarity. This expression was substituted in for (n_{sets} / f_{trips}) in our estimates of capture frequency in each stratum.

Estimating standard errors for capture frequency due to the entire fleet was problematic. For non-U.S. vessels, we only had the total number of target sets observed by stratum, and not the numbers of sets from each observed trip, so we were unable to estimate the variance in $\hat{N}_{sets}^{(Intl)}$. Thus, our estimates of capture frequency due to the entire fleet do not include estimates of standard error.

Because the research cruises all took place between 28 Jul and 10 Dec, we only used school size data from individual sets that occurred during the same time period, and our estimates of capture frequency are valid only for that period. However, if we assume that the same patterns in school sizes and tuna vessels' preference for school sizes hold for the entire year, then the annual capture frequency can be estimated using the corresponding annual set counts for U.S. and non-U.S. vessels. We did not attempt to make standard error estimates for these annual capture frequencies because, as above, we did not have the appropriate individual set data.

3.3 Independence of observations

Because of the geographically correlated nature of consecutive research vessel sightings or tuna vessel sets, successive school size observations from a single vessel may not have been independent. This is particularly a concern for the set data, because of the possibility of repeated sets on the same school (see Section 5.5). While dependence does not add a bias to our estimates, it does decrease the effective sample size, which affects our estimates of precision. We accounted for this problem by using bootstrap estimates of precision, and by defining our bootstrap resampling units so as to make them as independent as possible while keeping a reasonably large sample size. For research vessel data, we took days as the resampling unit, while for tuna vessels, we resampled by trips. For each bootstrap iteration, we resampled from the research vessel data to achieve approximately the same amount of search effort in each stratum as was actually achieved. We resampled from the tuna vessel data to achieve exactly the actual observed number of trips.

4. Results

4.1 School size estimation

Our estimate of the research vessel inter-observer size estimation variance parameter, τ^2, was 0.268. Thus, the adjusted mean school sizes were approximately $\exp(\hat{\tau}^2/2) = 14.3\%$ larger than the geometric means (which are biased low with respect to the true size). This value for τ^2 corresponds to an estimated coefficient of variation (c.v.) of 55% for the individual observers, and of 31% for the mean of three observers.

Figure 2 shows the estimated densities for school sizes as reported by the research vessel and tuna vessel observers. Note that Figure 2a represents $\pi^*(s)$ and not $\pi(s)$. While we fit separate densities for $p(s)$ in each of the two geographic strata, Figure 2b presents only a single, pooled estimate. The density estimates from the two strata were significantly different (Kolmogorov-Smirnov goodness of fit test, $p = 0.002$), but primarily at smaller school sizes, less than 200 animals. This difference had very little effect in absolute terms on the estimates of capture frequency for the two strata, and so we present only the pooled estimates for simplicity.

Both estimated densities were much smoother at large school sizes than at small school sizes. This is partially due to the variable bandwidth in the kernel estimator, but primarily due to the data themselves. The variable bandwidth algorithm was chosen in order to make reasonable density estimates in the right tails where there were few data, while not oversmoothing near the modes. We chose the bandwidth scaling parameters as a trade-off between smoothness and fit to the data.

As a check on the consequences of our decision not to stratify the school size density estimate for research vessel observers, we used Q-Q plots of school sizes between strata. These plots indicated that there was no substantial difference in distributions between strata for the research vessel observers. A Kolmogorov-Smirnov test also failed to detect differences in distributions between strata ($p = 0.62$).

4.2 Estimated effective strip halfwidth

Figure 3 shows the estimated values for the effective strip halfwidth as a function of school size. Because $\pi^*(s) \propto w_{eff}(s)\pi(s)$, $w_{eff}(s)$ represents the relative amount of "thinning" for schools of different sizes, i.e., $w_{eff}(s) / w$ is the probability of a school of size s being detected from the research vessel, given that it is within the truncation distance w. The estimated values indicate that approximately one third of schools of size 100 within the truncation distance (5.5km) were missed by the research vessel observers, while essentially all schools of size 1000 were detected. The result shown in Figure 3 is, qualitatively at least, partially constrained by the bivariate line transect model, i.e., if the data indicate dependence of detectability upon school size, then the parametric form for $w_{eff}(s)$ dictates that the estimated curve must vary smoothly and monotonically with size, and must approach w asymptotically. However, the model fit need not have any dependence on school size, and the specific direction and rate of increase shown in

Figure 3 are due to the data, and agree with observer experience in terms of reaching the limiting value within the range of sizes shown.

The standard error bars in Figure 3 exceed w in some cases, although it is not possible for $w_{eff}(s)$ to exceed the truncation distance w. These error bars are presented simply to represent the estimated precision for each estimate, and should not be interpreted as confidence intervals. Confidence intervals for the estimated halfwidths would tend to be asymmetric and would not exceed the truncation distance.

We did not stratify geographically in the bivariate line transect model to estimate $w_{eff}(s)$. One reason why the effective strip halfwidth might actually have differed between the two strata was a difference in observed sea state conditions. The average reported Beaufort sea state was between 2 and 3 for the inshore stratum, and between 3 and 4 for the middle stratum. We did fit the bivariate line transect model to data from the two strata separately, and found that the estimated effective strip halfwidth for the middle stratum was 10-20% smaller than that for the inshore stratum, depending on school size. This implies that detectability declined with increasing Beaufort state, and we concluded that our estimate of average $w_{eff}(s)$ was probably somewhat high if taken specifically for the middle stratum. However, we found that the number of observations in the middle stratum ($n_{schools}$ = 81) was too small to allow stratification and still have reasonable precision in estimating either $w_{eff}(s)$ or $\pi^*(s)$. The analogous bias for the inshore stratum was opposite in sign, but probably negligible in magnitude because most (83%) of the perpendicular distance data on which the estimate was based came from sightings in that stratum.

Although the on-effort trackline lengths in each stratum were roughly proportional to the stratum areas, if $w_{eff}(s)$ was indeed smaller for the middle stratum than for the inshore, then search effort, in terms of area, was weighted too much towards the inshore. This implies that our data may have included too high a proportion of sightings from that stratum. In the case of $\pi^*(s)$, there did not appear to be any difference between strata. However, our estimate of $w_{eff}(s)$, intended as an average over all research cruise legs, may have been overinfluenced by inshore stratum data. The practical impact is that our estimates of capture frequency for the middle stratum may be biased high. The effect on our estimates for the inshore stratum was probably negligible because of the high proportion of data from that stratum.

4.3 Estimated capture frequency

Figure 4 shows the estimated capture frequency due to U.S. tuna vessels. The estimates here represent the average number of times a school of a given size was set on each year during the four and one half month study period. In addition, although we computed separate estimates for the two geographic strata, they were so similar that we only present the pooled estimates here. Because both sighting and set rates were stratified geographically, the similarity between strata indicates that fishing pressure was approximately proportional to dolphin school density. As in Figure 3, the standard error bars are presented to indicate precision and should not be interpreted as confidence intervals.

The estimates in Figure 4 represent an integration of the information presented in Figure 2 and Figure 3, scaled by an estimate of the overall average capture frequency, i.e.

$$\hat{N}_{capture}(s) = \frac{\hat{N}_{sets}}{\hat{N}_{schools}} \cdot \frac{\hat{w}_{eff}(s)}{\hat{\pi}^*(s)\, w_{eff}} \cdot \hat{p}(s).$$

Note that w_{eff} in this expression actually cancels with a factor in the estimate of $N_{schools}$. The magnitude and direction of the trend in $N_{capture}$ was almost entirely due to the ratio of the estimates of $\pi^*(s)$ and $p(s)$. Estimates of the factor $w_{eff}(s)$ varied only by about 50% over the range of sizes considered, while the estimated capture frequency varied by two orders of magnitude.

The precisions of our estimates of capture frequency depended on the precisions of the individual estimated factors involved in the above expression. We were able to estimate those different precisions using the output of the bootstrap procedure and found that they varied widely. Much of the variability was in our estimates of $\pi^*(s)$, with bootstrap estimates of c.v. ranging from 9% at a school size of 100 up to 24% at 1000. Bootstrap c.v.'s for estimates of $w_{eff}(s)$ were low, ranging from 13% down to 1%, but, as mentioned above, $w_{eff}(s)$ was the factor most constrained by the model. Bootstrap c.v.'s for $p(s)$ were lower than those for $\pi^*(s)$, ranging from 14% at a school size 100 down to 6% at 1000. Set counts and sighting counts both had similar bootstrap c.v.'s, approximately 7% and 12% in the inshore and middle strata, respectively.

Finally, Figure 5 shows the estimated annual capture frequencies due to the U.S. fleet and due to the combined U.S. and international fleet. As before, the estimates in the two strata were very similar, and we present only a pooled set of estimates here. The estimate of the combined capture frequency for schools of size 1000 is 36.1 sets per year, or one set every 10 days, compared to well under once a year for schools of 100 animals. The estimate for the median school size set on (560 animals) was 10.1 sets per year, or just under once per month. The U.S. fleet accounted for an estimated 31% of sets during the years 1986-90. Although we were not able to estimate standard errors in this case, the error bars in Figure 4 should give at least a rough idea of the potential precision of these estimates.

Because of the extrapolation of school size distributions necessary to make annual and combined fleet estimates, the two curves in Figure 5 are identical in shape to that in Figure 4, but have different scale factors. The scale factor for the lower curve was an estimate of the overall (size-averaged) annual capture frequency, $N_{sets}/N_{schools}$, due to the U.S. fleet, while the scale factor for the upper curve was the corresponding estimate for the combined fleets. These two overall capture frequency estimates were not extrapolated from data collected during the study period, but were based on annual set counts for the two fleets.

Using the adjusted mean school sizes from the sighting data, and weighting by the estimated effective strip width, $w_{eff}(s)$, we made an empirical estimate of the cumulative proportion of individual dolphins in schools greater than or equal to a given size, i.e.,

$$H(s) \equiv \Pr\{\text{a dolphin is in a school of size} \geq s\} = \int_s^{\infty} \pi(t)dt$$

$$\hat{H}(s) = \frac{\sum_i \tilde{s}_i \hat{w}_{eff}(\tilde{s}_i) I\{\tilde{s}_i \geq s\}}{\sum_i \tilde{s}_i \hat{w}_{eff}(\tilde{s}_i)}, \qquad \text{where } I\{\tilde{s}_i \geq s\} = \begin{cases} 1, \text{ if } \tilde{s}_i \geq s \\ 0, \text{ otherwise} \end{cases}$$

and the sums are over research vessel sightings. We note that $H(s)$ should not be used to quantify the school size preferences of individual dolphins, and so, for example, while we estimated that schools larger than 1000 animals contained an estimated 9% of dolphins at any given time, this does not imply that the same 9% of dolphins always made up such schools.

Comparing $\hat{H}(s)$ with the combined capture frequency estimates (Figure 5, upper curve), schools of 1000 animals or greater were estimated set on at least once every ten days, and contained an estimated 9% of dolphins (Figure 6). Schools set on most often by tuna purse-seiners, containing from about 250 to 500 dolphins, were estimated to be set on between 2 and 8 times each per year on average; these schools comprised just under an estimated one third of the stock. An estimated one half of northeastern offshore spotted dolphins occurred in schools smaller than 250 animals; schools of this size were estimated to be set on less than twice per year each.

To interpret these results in terms of capture frequency for an individual dolphin, we must consider the size range of the schools with which a given individual tended to associate. If one assumes that dolphins have a strong fidelity for a characteristic school size, then the above results indicate that a fixed but relatively small proportion of the dolphin population was consistently subjected to a high rate of capture in purse-seine nets, while the majority of dolphins were subject to relatively little disturbance from the fishery. However, little is known about the spatial and temporal dynamics of dolphin schools and their sizes, and a range of other assumptions are possible.

At the other extreme, if school membership is completely fluid and dolphins mix perfectly among schools, then over the long term, all dolphins would experience the same capture rate. We made a rough estimate for this rate by estimating the total annual number of dolphins set on and the total number of dolphins. Using data from Table 2, a rough estimate for the mean annual number of sets on northeastern offshore spotted dolphins during the period of this study is 7610 sets per year. From tuna vessel observer data, an estimate for the mean school size for those sets is 773 animals. Combining these with an estimate for the total number of northeastern offshore spotted dolphins (Wade and Gerrodette, 1993) gives (7610 x 773 dolphins set on) / (731,000 dolphins) = 8.04 sets per dolphin per year.

The true picture certainly lies between these two extremes. If a given dolphin associates with schools from a range of sizes, then that animal's long-term rate of capture would be less than the estimated maximum rate of once every ten days, even though it may spend some time with the largest schools. On the other hand, if the composition and spatial location of some large schools are static over periods of weeks or longer, then animals in those schools could be subject to short-term capture rates even higher than our estimates because of the clustered distribution of fishing effort, leading to a higher probability of frequently repeated sets on the same school.

4.4 Capture frequency for very large schools

So few very large schools were observed by the research vessels (Figure 2a) that no kernel estimate of $\pi(s)$ was possible for s greater than 1000 animals. However, because the estimated detection probability for those schools was essentially one out to the truncation distance w, a rough calculation for capture frequency was possible. Assuming the effective strip halfwidth is equal to the truncation distance, an estimate of the average capture frequency due to the entire fleet is

$$\hat{N}_{capture}(s > 1000) \;=\; \frac{\hat{N}_{sets}^{(large)}}{\hat{N}_{schools}^{(large)}} \;=\; \frac{n_{sets}^{(US,\,large)}}{n_{sets}^{(US)}}\left(\frac{n_{sets}^{(US)}}{f_{trips}^{(US)}} + \frac{n_{sets}^{(Intl)}}{f_{trips}^{(Intl)}}\right)\frac{2Lw}{An_{schools}^{(large)}}.$$

The estimated average capture frequency due to the entire fleet for schools larger than 1000 animals was 39.1 sets per year, just slightly higher than the kernel-based estimate of capture frequency for schools of 1000 animals reported in Section 4.3 (36.1 sets per year). However, this rough estimate was somewhat unreliable because of the rounding tendency of tuna vessel observers, in this case an apparent preference for reporting a size estimate of 1000 rather than less “round” values just over 1000 (Figure 2b). This rounding had the effect of reducing the number of sets reported on schools larger than 1000 animals. Repeating this rough capture frequency calculation, but this time for schools greater than or equal to 1000 animals, gave an estimate of 51.3 sets per year. These estimates of capture frequency for very large schools correspond to capture in purse seine nets just under once a week.

5. Discussion

5.1 School size distribution correction

The probability of detection of a dolphin school from a research vessel was assumed to depend on school size, and the estimated parameters from the model indicated that detection probability increased with school size for any given perpendicular distance from the research vessel’s track line. To compensate, we used a correction to transform the “observed” distribution of school sizes, seen from the research vessels, into the “true” distribution. In effect, this correction increased the estimated number of smaller schools to account for their lower detectability. Although the model used to estimate this correction was based on previous work, the model has not been thoroughly explored, and in particular, its behavior for very small school sizes needs to be investigated further (Perkins and Gerrodette, in prep.). However, for the range of school sizes important in this analysis, we believe that the model gives a good indication of the size bias inherent in the observations.

In any case, it is clear that whatever the specific form of the correction, it can only shift the distribution of observed school sizes towards smaller schools. Were we to have ignored the size selection bias in the research vessel data entirely, the magnitude of our quantitative results for capture frequency would have been reduced somewhat, i.e., we would have estimated a lower capture frequency for each school size. However, the results would have remained qualitatively unchanged.

5.2 Observer size estimation errors

Our statistical model for the school size data included terms for selection biases, that is, which schools were included in the sighting or set data, as discussed in Section 3.1. However, there was also a potential for observer size estimation biases. That is, given a sighting of, or a set on, a specific school, an observer had to estimate its size. We assumed that there was no systematic tendency for either tuna vessel or research vessel observers to over- or underestimate the true school sizes, and treated the observer estimates (or adjusted mean estimates) of school size as exact counts (Section 3.2). Thus, we did not include an error term for size estimates in either the kernel density estimates of $\pi^*(s)$ and $p(s)$ or the bivariate line transect estimates of $w_{eff}(s)$. In this section, we discuss the implications and validity of this assumption.

Observer estimation bias or variance would affect our estimates of $\pi^*(s)$ and/or $p(s)$. A systematic tendency for observers to over- or underestimate would scale or otherwise deform those estimated densities, depending on whether the bias was proportional to size or was more complex. Even if the observers were unbiased in their individual estimates, estimation variance would still increase both tails in the density estimates. Thus, if research vessel observers and tuna vessel observers consistently made different errors in estimating school sizes, then the trend in our estimates of capture frequency, e.g. Figure 4, could have been in part or entirely due to those errors. We describe below a statistical model which we used to qualitatively characterize observer estimation errors.

To investigate the magnitude of observer estimation errors, we assumed a multiplicative lognormal error model, i.e., the j^{th} observer's estimate of the i^{th} school is $s_{ij} = s_i e_{ij}$, where s_i is the true school size, $\ln(e_{ij}) \sim N(\nu, \tau^2)$, and ν may depend upon s_i. Under this model, s_{ij} has an expected value of $s_i \exp(\nu+\tau^2/2)$ and a constant c.v. Estimation bias is directly proportional to size when ν does not depend upon s_i, and the special case $\nu = -\tau^2/2$ (a negative bias on the log scale) corresponds to unbiased estimation. When there are k_i independent replicate observations, their geometric mean is lognormally distributed, i.e., $\ln(\tilde{s}_i) \sim N(\nu, \tau^2/k_i)$. On the other hand, the adjusted mean is not, and so the geometric mean is more convenient for investigating this error model. We note that our choice of the adjusted mean as an estimator of s_i in our main analysis was based on the assumption of unbiased individual estimates. Under that assumption, the geometric mean is not an appropriate estimator of s_i because it has expectation $s_i \exp(-(1-1/k_i)\tau^2/2)$.

Because lognormal errors have a skewed distribution, their variance would increase the right tail of our estimates of $\pi^*(s)$ or $p(s)$ more than the left, in absolute terms. However, if the true size distributions are roughly lognormal, the estimated densities would remain qualitatively the same, i.e., roughly lognormal, and, for example, the means of the estimated densities would not be higher than the true means unless there is also a positive bias.

(a) Research vessel observers

Gerrodette and Perrin (1991) studied dolphin school size estimation errors for research vessel observers by ground-truthing observer estimates against aerial photo counts of the same school. That study used observations from the NMFS research cruises ($n_{sightings}$ = 171) for which clear, unambiguous photos had been taken. Treating the photo counts as exact, they found that the counts from a single observer could be modelled as lognormally distributed given the true school size. They also found that a given observer in the study might have a substantial positive or negative bias. However, they concluded that it would be possible to bias-correct estimates from an observer, given appropriate ground-truth data.

Using their photo/observer dataset, we fit a lognormal model for the geometric means of the observer estimates from each sighting. The particular model we used for the bias was $\nu = a+b\ln(s_i)$, i.e., a linear regression on the log scale, which corresponded to an expected value of $s_i^{1+b}\exp(a+\tau^2/2)$ on the original scale. The fit showed evidence for a progressive tendency towards underestimation of the sizes of larger schools, with the estimate of b small but negative (-0.082, s.e. = 0.023). Specifically, the fit indicated that the observers had essentially no bias at a true school size near 100, but that there was a negative bias of 21% at a school size of 1000. The estimated c.v. for the geometric means, given the true size, was 48%. Thus, the size-dependent bias would tend to shorten only the right tail of our estimate for $\pi^*(s)$, while, as pointed out above, the estimation variance would tend to lengthen both tails.

Using Lilliefors' test for normality, we found that the geometric means of the estimated school sizes, given the true school size, were consistent with the assumption of normality on the log scale ($p = 0.15$). We note that the individual observer estimates, when pooled across all observers ($n_{estimates}$ = 939), were significantly non-lognormal ($p = 0.04$). However, this is not unexpected given the large sample size, which implies a high power to detect even small departures from the assumed idealized distribution. We also note that the estimated variance parameters for the fits to the individual observer estimates and to the geometric means suggested that the individual observer estimates were not true replicates. This implies that there was a significant source of variation in the estimates that was not due to the individual observers, e.g., ocean conditions or school behavior.

Given this information, it would have been possible in theory to bias-correct the research vessel observer size estimates for our estimates of $\pi^*(s)$ and $w_{eff}(s)$. However, because data on which to base a similar adjustment for tuna vessel observers (see below) did not exist, we did not make such a correction. In addition, the bias analysis here is only a preliminary effort.

(b) Tuna vessel observers

Quantifying observer estimation errors in the tuna vessel set data was not possible as it was for research vessel data. Although there have been several experiments carried out to investigate school size estimation from tuna vessels, no suitable study similar to that of Gerrodette and Perrin (1991) has been carried out to ground-truth the tuna vessel observer data used in this analysis. Allen et al. (1980; see also Scott et al.,1985) reported on data collected to compare ship-based observer estimates, aerial observer estimates, aerial photo counts, and backdown counts of schools that were set on by a chartered tuna vessel. There were few observations ($n_{sets} = 5$) which could be used to compare ship-based observer estimates of an entire school to photo counts. There were 30 sets with both ship-based observer estimates and backdown counts, however, 10 of those were from sets where less than 80% of the school was captured. In addition, the data were collected under conditions that differed somewhat from actual fishing operations. No analysis was done to compare ship-based observer estimates to either photo counts or backdown counts. Thus, those data do not directly help in quantifying the bias and variance of the tuna vessel observer "best estimates" used in this analysis.

While ground-truth data to quantify tuna vessel observer estimation errors has not been collected, qualitative results from the research vessel observer ground-truth data of Gerrodette and Perrin (1991) may be applicable. However, differences between the two types of observers and observing conditions should be noted. Both observer programs have extensive training, however, because of the large number that are needed, up to 15% of tuna vessel observers in the field are on their first cruise[1], while all of the research vessel observers had some previous experience[2]. In addition, research vessel observers were isolated as much as possible from any outside influences on their estimates, e.g., teams of observers were strictly trained not to discuss their estimates amongst each other. In contrast, tuna vessel observers are in constant contact with crew members and it is possible that their estimates were influenced by the rough size estimates typically made by the crew during a set[3]. Research vessels regularly approached schools for the sole purpose of making size estimates and species identification. On the other hand, dolphin schools are often intentionally or unintentionally split up during a set, and tuna vessel observer school size estimates are in general a combination of backdown counts and estimates of the number of animals not encircled by the net (IATTC, 1991).

Finally, there was only a single observer aboard each tuna vessel to make school size estimates for sets, while the size estimates from research vessel sightings were the mean of typically three estimates. As mentioned above, Gerrodette and Perrin (1991) found that research vessel observer estimates could be modelled as lognormally distributed about the true school size. If the same conclusion holds for tuna vessel observers, it is possible that their observed distribution of school sizes is too heavy-tailed because of the estimation variance effect as discussed above. Because we used means for the research vessel estimates, the effect would have been reduced in those data

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1) Personal communication, Dr. Martin Hall, Inter-American Tropical Tuna Commission, La Jolla, CA.
2) Personal communication, Dr. Jay Barlow, Southwest Fisheries Science Center, La Jolla, CA.
3) The influence of others on an observer's size estimates should not be discounted. The tendency of research vessel observers during early research cruises to alter their school size estimates after discussing them with one another was one factor that led to the current policy of not discussing estimates among observers (personal communication, Dr. Jay Barlow, Southwest Fisheries Science Center, La Jolla, CA).

because of the resulting smaller variance. We did make an estimate of $\pi^*(s)$ based on the individual research vessel observer estimates, however, it was still much less weighted towards large schools than was our estimate of $p(s)$. We concluded that the variance of tuna vessel observer estimates was not the main cause of the difference between our estimates of $p(s)$ and $\pi^*(s)$.

In the absence of any ground-truth studies for tuna vessel observers, a comparison of relative biases between the two types of observers would have been useful. Cologne and Holt (1984) compared observers with experience only on research vessels to observers with experience only on tuna vessels. They concluded that there was no relative school size estimation bias between observer types. However, the experiment was carried out entirely on a research vessel, and it is possible that the conditions under which tuna vessel observers work are a factor in any bias in their estimates. Cologne and Holt did not have any data with which to investigate absolute biases.

We considered comparing the distribution of estimated school sizes in research vessel sighting data and tuna vessel sighting data (as opposed to set data) to determine if a relative bias in size estimation existed between the two types of observers. Obviously, tuna vessel set data could not be used for this purpose because of the “selection bias” present in the tuna vessel data, i.e., the tendency of fishermen to set on larger schools. Unfortunately, we concluded that tuna vessel sighting data were also unsuitable for such a comparison. In particular, tuna vessel observers do not search for schools in the same way as the research vessel observers, e.g., they do not use high-power binoculars and must rely on crew reports for at least some schools. It would be difficult to separate out these differences from any size estimation bias. More importantly, tuna vessels do not search randomly (as the research vessels did) and so sightings from tuna vessels are likely to represent a biased sample (relative to the research vessels) if localized areal differences in school size distribution exist.

It was possible to compare school size estimates of tuna vessel observers to those of the crew. A rough fit to the logs of the two types of estimates indicated that, for schools that were set on, the crew’s estimates were 33% higher on average than those from the trained observers (Figure 7). While the crew members were not trained scientific observers, this relative bias between school size estimates from two different sources provides a clear example of the potential for observer bias.

5.3 Spatial distribution of schools

Our analysis can be taken to imply full spatial mixing, that is, all schools of a given size within a stratum have the same probability of being set upon. A more realistic model is that some schools have a higher or lower probability depending not only on their size, but also on their average spatial location relative to areas of high school density or high fishing effort. Other factors such as seasonal effects and the amount of associated tuna are also interrelated with geographic location in determining the rate of capture for a given school. Because we only included a limited spatial component in our model, the appropriate interpretation of our results is that we estimated an average probability of being set upon, as a function of school size, for schools within each stratum.

(a) Large-scale trends in school size

Observer experience suggests that pressure from fishing on dolphin can reduce average dolphin school size, i.e., areas of high fishing effort tend to have smaller schools[1]. This may be a result of chase and capture operations during sets intentionally or unintentionally splitting schools into smaller subgroups[2]. However, we did not find any indication of such a trend in our northeastern offshore spotted dolphin school size data.

To help detect such a relationship, we spatially smoothed the school size data from both tuna vessel sets and research vessel sightings, using local quadratic regression (Cleveland and Devlin, 1988) on the log scale. Treated separately, both sets of data showed some evidence for locally correlated spatial differences in average school size, however three points should be noted. First, there was no clear geographically predictable trend related to, for example, latitude or distance offshore. The trend surface in both cases was apparently random, although we did not attempt to relate average school size to any environmental predictors such as sea surface temperature. Second, both data sets were somewhat sparse. The tuna vessel data were numerous but highly clustered: over three quarters of all observed sets occurred in less than 16% of the stock range. The research vessel data were more evenly distributed, but still had many large gaps between sightings, on the order of hundreds of miles. Third, although in both cases the spatial regressions did detect patterns in average school size, the estimated random component at any particular spatial location was nearly as large as the entire range of the estimated trend component. Thus, either fitted trend surface was a very imprecise predictor of size given position for a particular school.

Comparing either of the two fitted surfaces for average school size to a spatial plot of fishing effort did not reveal any relationship. The average school sizes from either research vessel sightings or tuna vessel sets did not appear to be related to the local level of fishing effort. Finally, the two fitted trend surfaces had no apparent similarity to each other. We concluded that if fishing pressure did affect spotted dolphin school size, its effects may have been masked by size selection in the tuna vessel set data, and by the relatively limited number of observations in the research vessel sighting data.

(b) Clustering and non-random search effort

Other analyses of tuna vessel observer data have shown some evidence for so-called “hot spots”, i.e. a patchy environment leading to unpredictable, localized regions supporting high dolphin densities and/or large dolphin schools[3]. However, the research vessel data in this study were neither numerous nor dense enough to investigate trends on such small scales. The tuna vessel

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1) Personal communication, Rand Rasmussen, Southwest Fisheries Science Center, La Jolla, CA.
2) Personal communication, Dr. Martin Hall, Inter-American Tropical Tuna Commission, La Jolla, CA. Depending on how long such a school remains fragmented, how completely it reaggregates, and how soon and how frequently it is set on again, this effect could complicate interpretation of capture rate as a function of school size. Some limited data have been collected to study school fragmentation and reaggregation (Perrin et al., 1979; Personal communication, Dr. Mike Scott, Inter-American Tropical Tuna Commission, La Jolla, CA.
3) Personal communication, Dr. Martin Hall, Inter-American Tropical Tuna Commission, La Jolla, CA.

data did have some groups of observations consistent with the presence of hot spots. Two examples are discussed in Section 5.5.

5.4 Characterizing dolphin schools

(a) Variation in school size over time

The simplest interpretation of this analysis would assume that a dolphin school is a fixed entity which does not change in size, and so the average capture frequency is well defined for each school and each member of a school. If, on the other hand, schools often fragment and reaggregate, then interpretation is more complicated. For example, one study has shown a diel trend in ETP dolphin school sizes (Scott and Cattanach, in press). The research vessel sighting data used here did not show similar clear evidence for such a trend, possibly due to a smaller sample size.

The superpopulation model that we assumed (Section 3.1) is one way to account for this fluid nature of dolphin schools. In particular, the research and tuna vessel school size data represent time-averaged samples, i.e., averages over repeated realizations from the superpopulation. Thus, although school sizes (or at least the composition of individual dolphins in a given school) probably did not remain static over time, we were estimating their underlying distributions.

(b) Species composition

Most schools in both the research vessel and tuna vessel data included not only northeastern offshore spotted dolphins, but other species as well, primarily spinner dolphins (*Stenella longirostris*). We did not differentiate between pure and mixed schools in our analysis. Thus, we took as our population of schools not just those composed purely of northeastern offshore spotted dolphins, but all schools containing them. School sizes were taken as the total number of animals in each school. This approach would not have been appropriate if we had been estimating a stock-specific abundance (e.g., Wade and Gerrodette, 1993). However, as long as there is no bias in the species composition of schools that are set on, our approach is valid. An exploratory data analysis indicated that the distribution of species proportions was very similar for both sources of data.

There was some indication that pure spotted schools tended to be smaller on average than mixed spotted/spinner schools. We did not pursue this because it did not affect our results.

5.5 Encounter rate for very large schools

Inspection of Figure 2 raises the question of why so few very large schools (1000 animals or greater, say) were sighted from the research vessels when so many were set upon by tuna vessels. Only five schools (1% of sightings) in that range were reported by research vessel observers, and the largest was estimated to be 2617 animals. 896 schools (26% of observed sets) in that range were reported set upon by tuna vessel observers, and 97 were estimated to be larger than 2617. These largest schools from the set data did tend to include slightly higher percentages of species other than spotted dolphins. However, they were still primarily made up of spotted dolphins (just over an estimated 70% on average), and it was not the case that they were due to an association with large groups of, for example, common dolphins (*Delphinus delphis*), which are known to form very large schools (e.g. Edwards and Perrin, 1993).

At least four explanations for this apparent discrepancy are possible. First, this may simply reflect the much greater search effort by tuna vessels and their preference for setting on large schools. If research vessel effort were increased, perhaps at least some schools larger than 3000 animals would be reported. Second, part of the difference may be due to relative bias in size estimation between the two types of observers, as discussed in Section 5.2. However, to explain all of the difference, the two sets of observers would have to differ on average by a factor of five in their estimates, not a likely possibility. Third, the research vessels may have missed a relatively rare segment of the population of schools, which the tuna vessels are able to seek out with a non-random search strategy. Fourth, some of these large observations in the set data may have been from intentionally repeated sets on the same schools.

Evidence for either of these last two explanations appears in the set positions in the observer data from U.S. tuna vessels. Figure 8 shows a cluster of eighteen sets which occurred very close together in both space and time. Eleven of those sets had estimated school sizes in the 99th percentile of sizes observed from the research vessels. It seems unlikely that if schools of such a size were fairly evenly distributed, tuna vessels would be able to set on more within three days, in a small area, than the research vessels detected in seven years over the entire stock range. An even more extreme example is shown in Figure 9, where over two days, a single tuna vessel made sets on four schools with estimated sizes larger than all but four of the schools detected by research vessels over seven years. Given the time sequence of estimated sizes, one plausible explanation is that the vessel repeatedly set on a single very large school which became more and more fragmented. Both of these examples were chosen as somewhat extreme cases, but they serve to illustrate the possibility that localized areas of high density and/or school size may exist, and that repeated sets on a single school may occur. Either of these two possibilities imply that some very large schools may be set on once or more a day over several consecutive days, by one or more tuna vessels.

5.6 Estimation of $N_{schools}$

The local dolphin school density in the ETP changes over short time scales in response to ocean environmental factors. Because of this and the dynamic nature of dolphin school sizes, the estimate $\hat{N}_{schools} = An_{schools} / 2L\hat{w}_{eff}$ implicit in our estimate of $N_{capture}$ should not be thought of as a "sampling-based" finite population estimator of a fixed total. In that context, as more area is observed, the sampling fraction increases to one and the population should become known exactly with no uncertainty. In practice, more independent samples do increase the precision of the estimator. However, because of population movement and the limited area that can be instantaneously sampled, its variance cannot be reduced to exactly zero, even with exhaustive sampling of the stock range. In addition, the number of schools is not likely to be constant over time. Thus, the quantity of interest was not the configuration of schools at a given moment, but rather the mean total number for an assumed steady state. Our interpretation of $\hat{N}_{schools}$ was as an estimate of average density (over both location and time), $n_{schools} / 2L\hat{w}_{eff}$, times a known area, and we did not include a finite population variance correction in any of our computations.

The research cruises used the same survey design for 1986 through 1990. However, the ships' cruise tracks were not precisely the same from year to year. Because of this and the dynamic nature of local dolphin school densities, we treated all seven cruises as independent random (with respect to the dolphin population) samples, and combined sighting counts and search effort to make a single estimate of the average $N_{schools}$. Of course, if the cruise tracks were biased with respect to large scale geographic differences in density, then the first five cruises probably could not be considered independent replicates. However, the surveys were designed with approximately even coverage within each stratum to minimize this sort of bias.

5.7 Estimation of N_{sets}

Unlike the case of $N_{schools}$, estimating N_{sets} could be treated as a problem in finite population statistics, because the realized number of sets for a particular year was probably of more interest than the expected number. In contrast to the local density of dolphin schools, the number of target sets for any fishing trip was a well-defined, fixed quantity, and with 100% observer coverage of trips, the total number of target sets for any given year would have been known exactly.

On the other hand, the realized school sizes from sets were not of primary interest, rather, it was their underlying distribution, $p(s)$, that needed to be estimated. Unfortunately it was not practical to combine a finite population bootstrap algorithm, to account for sampling-based variance in $\hat{N}_{sets}$, with a standard bootstrap algorithm, to account for variance in $\hat{p}(s)$, while still resampling at the level of trips to approximate independence between bootstrap units. Thus, we interpreted our estimate of N_{sets} as an estimate of the expected number of sets, and used model-based methods throughout. The usual point estimates for the realized number of sets and the expected number of sets are identical, $\hat{N}_{sets} = N_{trips} n_{sets} / n_{trips}$, however their variances have different forms and interpretations. In particular, with a significant sampling fraction, the sampling-based variance is smaller due to the finite population correction factor. Thus our bootstrap standard errors for capture frequency are conservative if one chooses to interpret $\hat{N}_{sets}$ as an estimate of the realized number of sets.

However, by rerunning the analysis with N_{sets} fixed and assumed known (equal to n_{sets}/f_{trips}), we found that the variability in $\hat{N}_{sets}$ contributed very little to the variability of $\hat{N}_{capture}(s)$. This implies that the variability in the estimates of $N_{schools}$, $\pi(s)$ and $p(s)$ dominates the standard errors for $\hat{N}_{capture}(s)$, and that even if N_{sets} were known exactly, those standard errors would not improve significantly.

Implicit in our estimate of N_{sets} was an estimate of the mean number of target sets per trip. Because we stratified set counts geographically, there were actually two such mean estimates, $n_{sets}^{(inshore)} / n_{trips}$ and $n_{sets}^{(middle)} / n_{trips}$. We note that while n_{sets} was stratified, neither N_{trips} nor n_{trips} was because trips were not restricted to a single stratum. Using number of fishing days as a covariate would probably have resulted in more precise estimates of N_{sets} in each stratum because

n_{days} could have been stratified and because the number of target sets per fishing day in a particular stratum is much less variable than the number of sets per trip. However, the total number of fishing days by stratum was not known. Using commercial catch as a covariate may also have improved the precision of the estimates somewhat, but total catch by stratum was not known.

As pointed out in Section 3.2, we were able to make estimates of standard error for capture frequency due to the U.S. fleet during the study period, but not for the extrapolations to the entire fleet or to annual capture frequency. This was because we did not have the individual set observations with which to quantify variance in n_{sets}, except in the case of U.S. tuna vessels. It may have been possible to make the assumption that $\mathrm{var}[n_{sets}] \propto \mathrm{E}[n_{sets}]$ with the same proportionality constant for both the U.S. and international fleets, and to estimate the variance in n_{sets} for the international fleet by rescaling corresponding estimates for the U.S. fleet. This simple rescaling would have been sufficient if we had just been estimating N_{sets}, but it could not be extended to the more complex bootstrap framework for our estimate for capture frequency.

We note that the study period was only four months long each year, and partial “censoring” (i.e. considering only those sets that occurred during the study period) affected a significant percentage of trips. On the other hand, censoring was a relatively minor effect when considering the entire five year period in making annual estimates. Thus, the estimates of N_{sets} for the two different periods really come from different populations of fishing trips. This does not cause a problem because, as pointed out above, the estimate of N_{sets} is based on an implicit estimate for the mean number of target sets per trip, and the definition of “target set” simply changes for the two different periods.

5.8 Conclusions

The results of this study indicate that tuna purse-seiners in the ETP fishing on northeastern offshore spotted dolphins do indeed have a strong preference for setting on larger than average dolphin schools, and that such schools were subject to being set on at a much higher rate than were smaller schools. Specifically, the largest schools considered, those of 1000 animals, were estimated to be set on approximately once every ten days, while the smallest schools considered, those of 100 animals, were estimated set on less than once a year. Our estimated capture rates should be taken as averages for a given school size, and do not account for variation due to other factors such as geographic location. Also, while we estimated rates in terms of sets per year, we do not assert that the short-term capture rate for a given school is constant, i.e. that sets occur at evenly spaced intervals.

To draw conclusions about capture frequency for an individual dolphin, we must consider the size range of the schools with which a given individual tends to associate. Our results imply that dolphins who associate primarily with large schools will be subjected to capture much more often than individuals who associate primarily with small schools. However, we also estimated that the largest schools are relatively rare, and account for a minority of the total number of individual dolphins at any given time. These results may imply that a fixed but relatively small proportion of the dolphin population was consistently subjected to a high rate of capture in purse-seine nets, but that a majority of dolphins occur in schools smaller than those apparently preferred by purse-seiners, and experience relatively few captures per year.

However, little is known about the spatial and temporal dynamics of dolphin schools and their sizes, and other conclusions are possible. If dolphins associate with a wide range of school sizes, then the capture rates for individual dolphins would tend to “average out” and so would vary less than the range of capture rates for schools. On the other hand, there are other factors affecting the rate of capture for a school, such as geographic location or the amount of associated tuna. Differences in these factors between schools could lead to short-term individual capture rates even higher than our estimates because of the clustered distribution of fishing effort leading to frequently repeated sets on the same school.

While quantifying these capture frequencies does not provide any direct measure of fishery-related stress, we hope that the analysis may provide in the future at least a preliminary basis for estimating stock-wide effects of (yet-to-be-measured) individual-based physiological stress responses.

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Figure 1. Geographic stock boundaries for the northeastern offshore spotted dolphin (*Stenella attenuata*). The stock is defined by the region in the ETP north and east of 5°N and 120°W, bounded at 28°N. The two strata pictured are based on those defined by Holt et al. (1987). The inshore and middle strata have total areas of 4,544,000 km^2 and 2,019,000 km^2, respectively. Points represent on-effort sightings from the research vessels, 1986-90 and 1992-93.

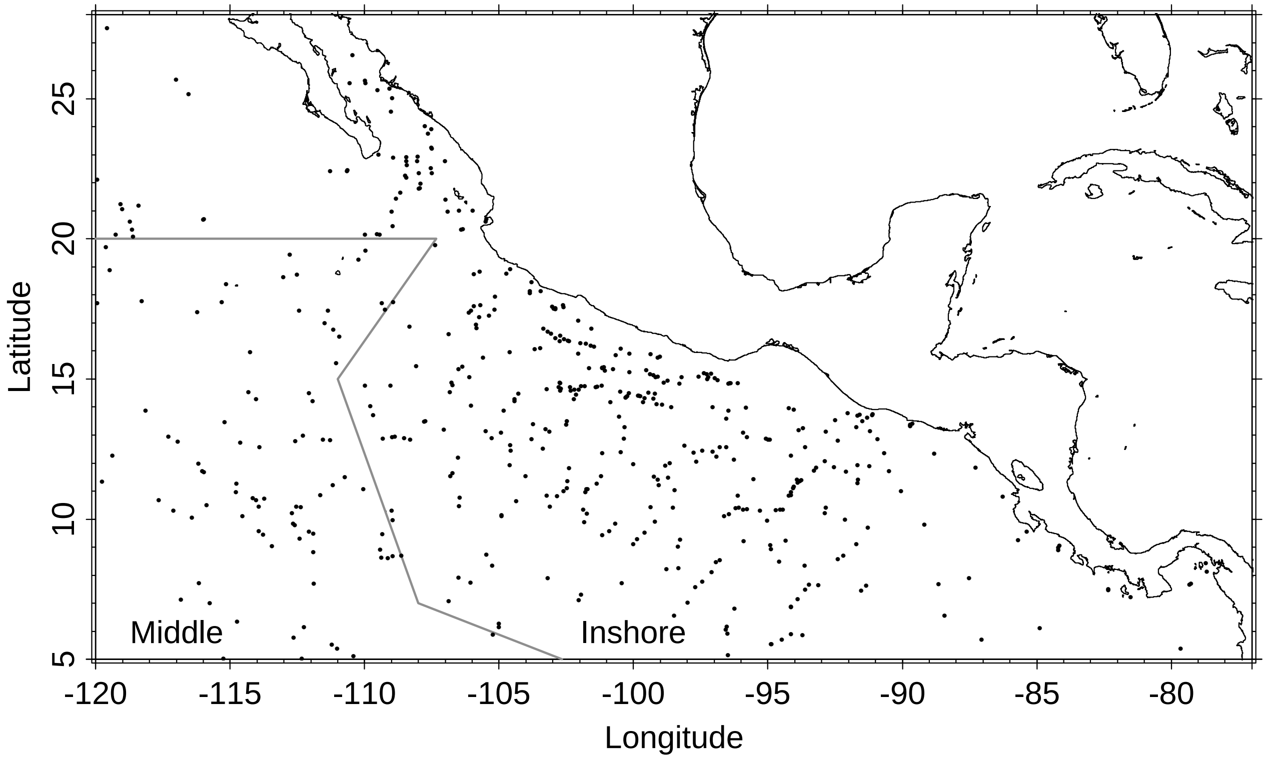
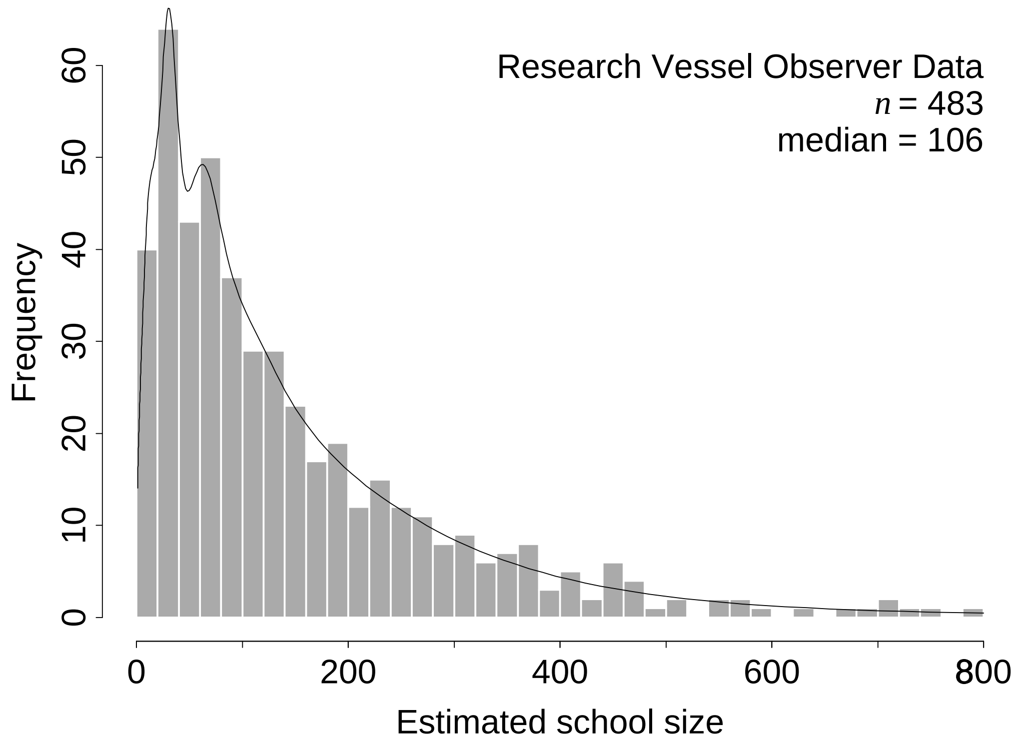


Figure 2. Distribution of estimated observed school sizes for northeastern offshore spotted dolphins. These data include observations from both strata. The fitted lines are kernel estimates of smooth densities for these observations. Note the different x- and y-axis scalings. (a) Research vessel sightings, 1986-90 and 1992-93. These data are the adjusted mean estimates (see text, Section 3.2), and include on-effort sightings with perpendicular distance < 5.5km. 8 observations > 800 not shown. (b) Tuna vessel sets, 1986-90. 19 observations > 4000 not shown.

(a)



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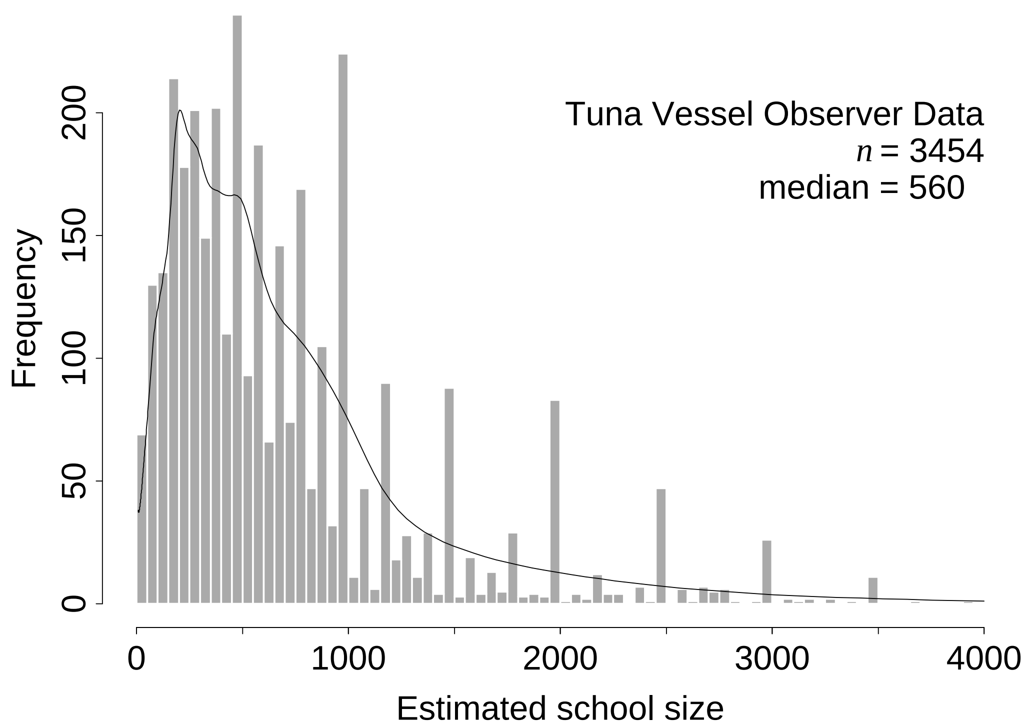

Figure 3. Estimated effective strip halfwidth as a function of dolphin school size. These maximum likelihood estimates are from the bivariate hazard rate line transect model as discussed in the text, and are based on northeastern offshore spotted dolphin school sightings from observers aboard NMFS research vessels during the months July to December, 1986-90 and 1992-92. Error bars indicate plus or minus one standard error, and should not be interpreted as confidence intervals. The horizontal line at 5.5 km indicates the perpendicular truncation distance in the line transect model.

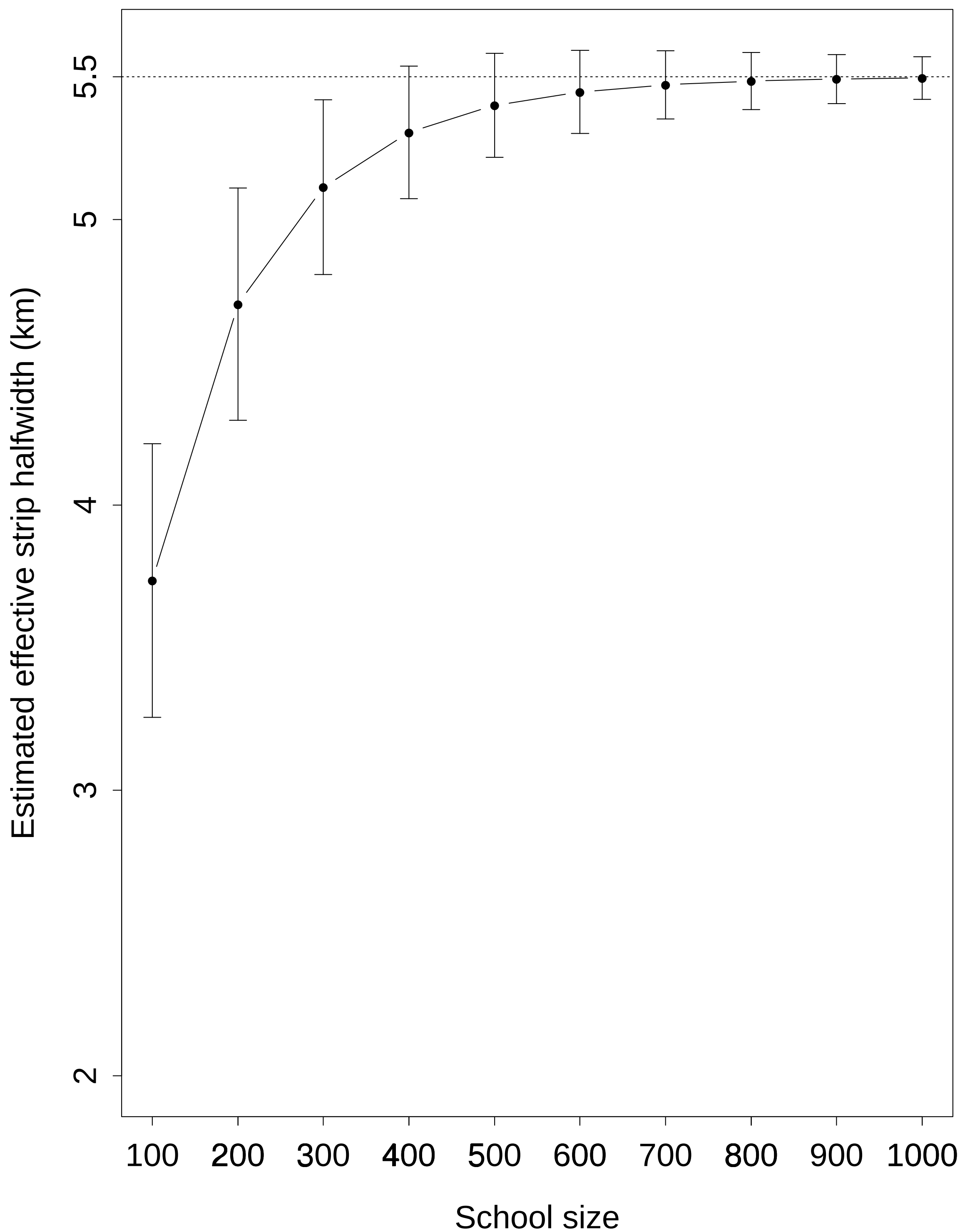

Figure 4. Estimated capture frequency as a function of dolphin school size, for schools of northeastern offshore spotted dolphins. The estimates are of the average number of times a school was set on each year by U.S. tuna purse-seiners, between 28 July and 10 December (19.4 weeks), for the years 1986-90. Error bars indicate plus or minus one standard error, and should not be interpreted as confidence intervals.

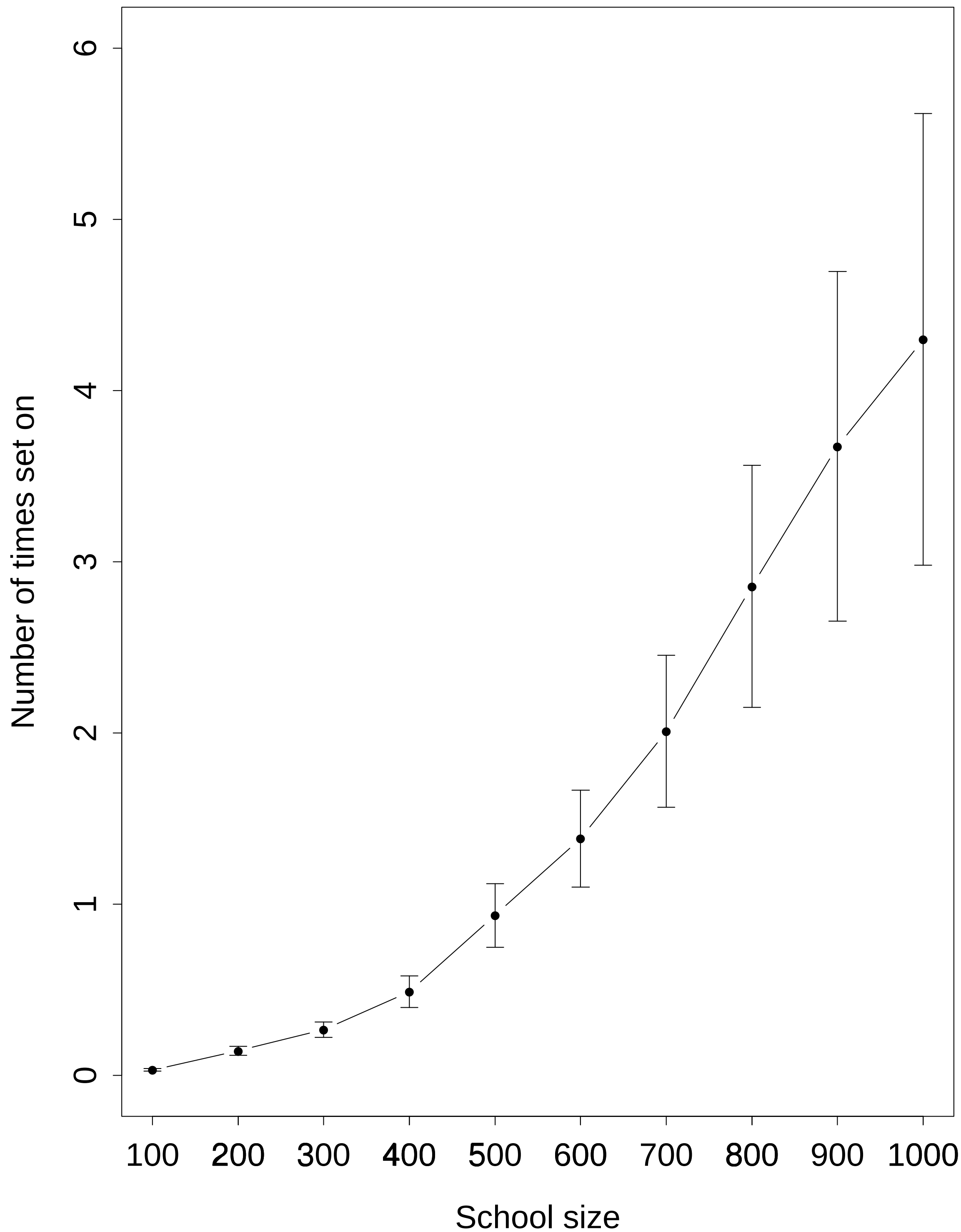

Figure 5. Estimated annual capture frequency as a function of dolphin school size, for schools of northeastern offshore spotted dolphins. The estimates are of the average number of times a school was set on each year by tuna vessels in the ETP purse-seine fleet, for the years 1986-90. The lower curve shows the number of sets due to U.S. vessels only, and the upper curve shows the number of sets due to U.S. and non-U.S. vessels combined. Estimates of standard error were not possible for these estimates.

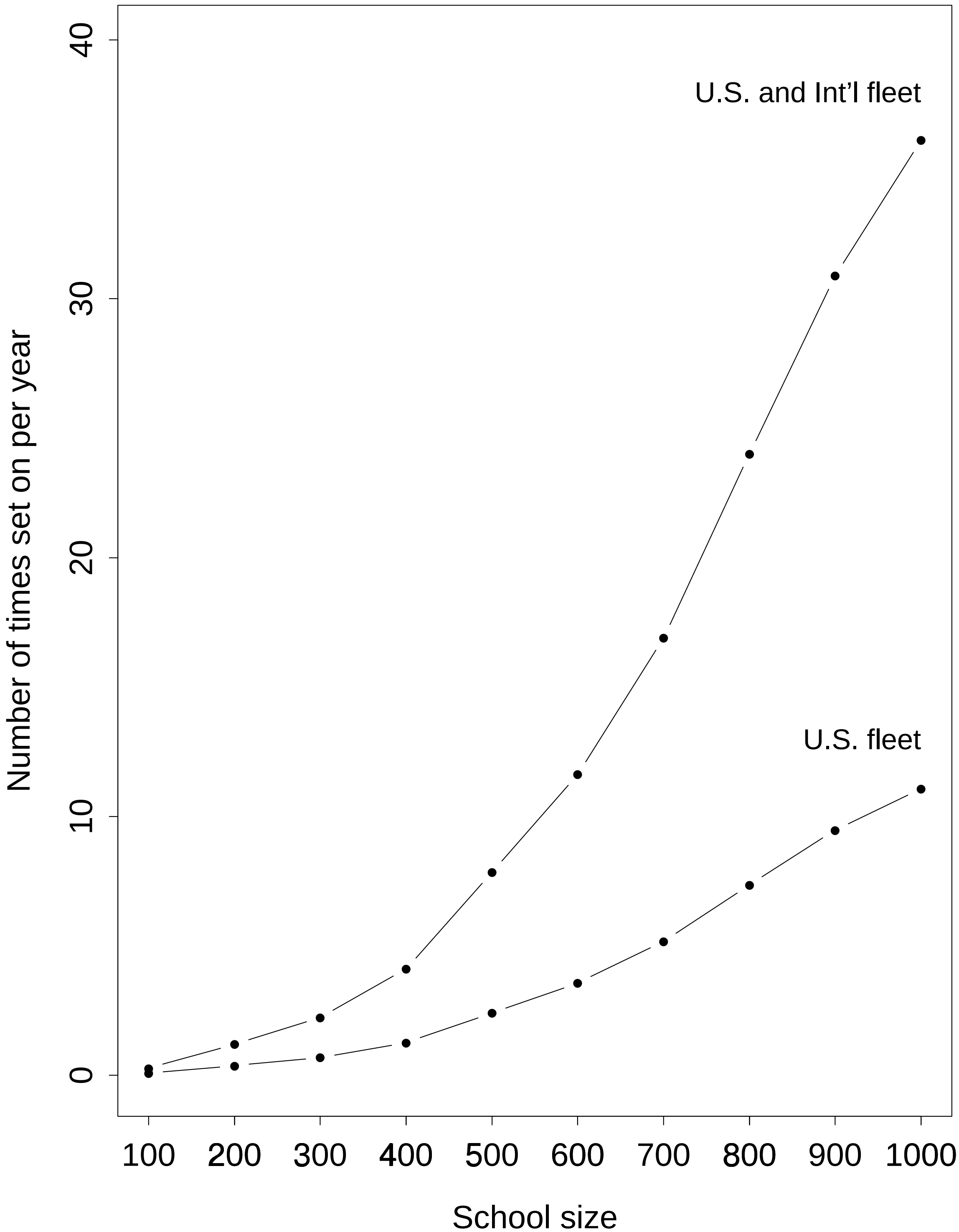

Figure 6. Estimated proportion of northeastern offshore spotted dolphins subject to different levels of capture frequency. The horizontal axis represents a minimum number of times set upon per year by U.S. and non-U.S. tuna vessels in the ETP purse-seine fleet, for the years 1986-90. The vertical axis represents the estimated proportion of the stock (<u>not</u> the proportion of schools) subject to at least that rate of being set upon. *s* is the minimum school size accounting for that proportion.

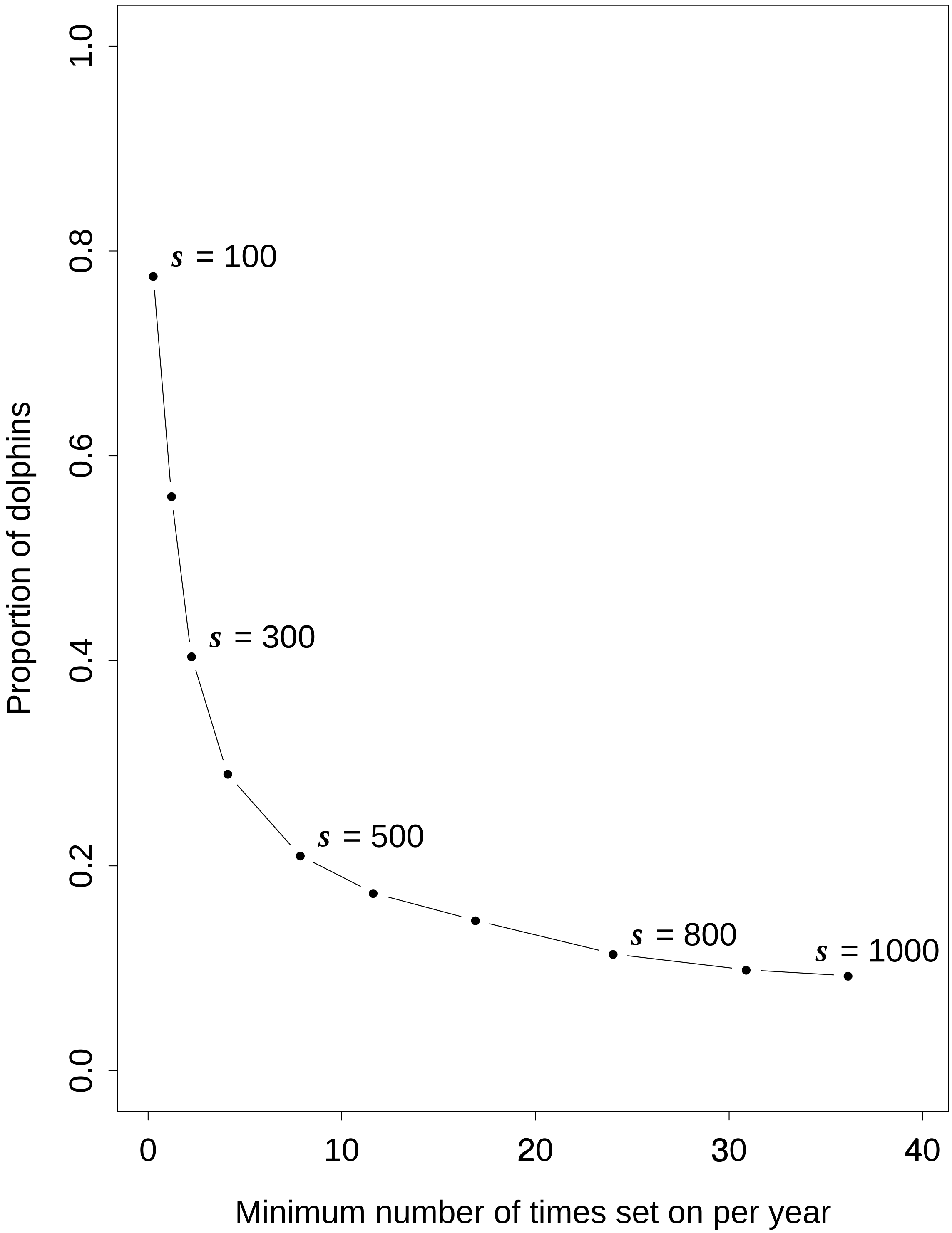

Figure 7. Crew's school size estimate vs. observer's best school size estimate for northeastern offshore spotted dolphin schools set on by U.S. tuna purse seine vessels, 1986-90. The sets were observed by either NMFS- and IATTC-trained scientific observers. Fitted line is $s_{crew} = 1.33 * s_{observer}$

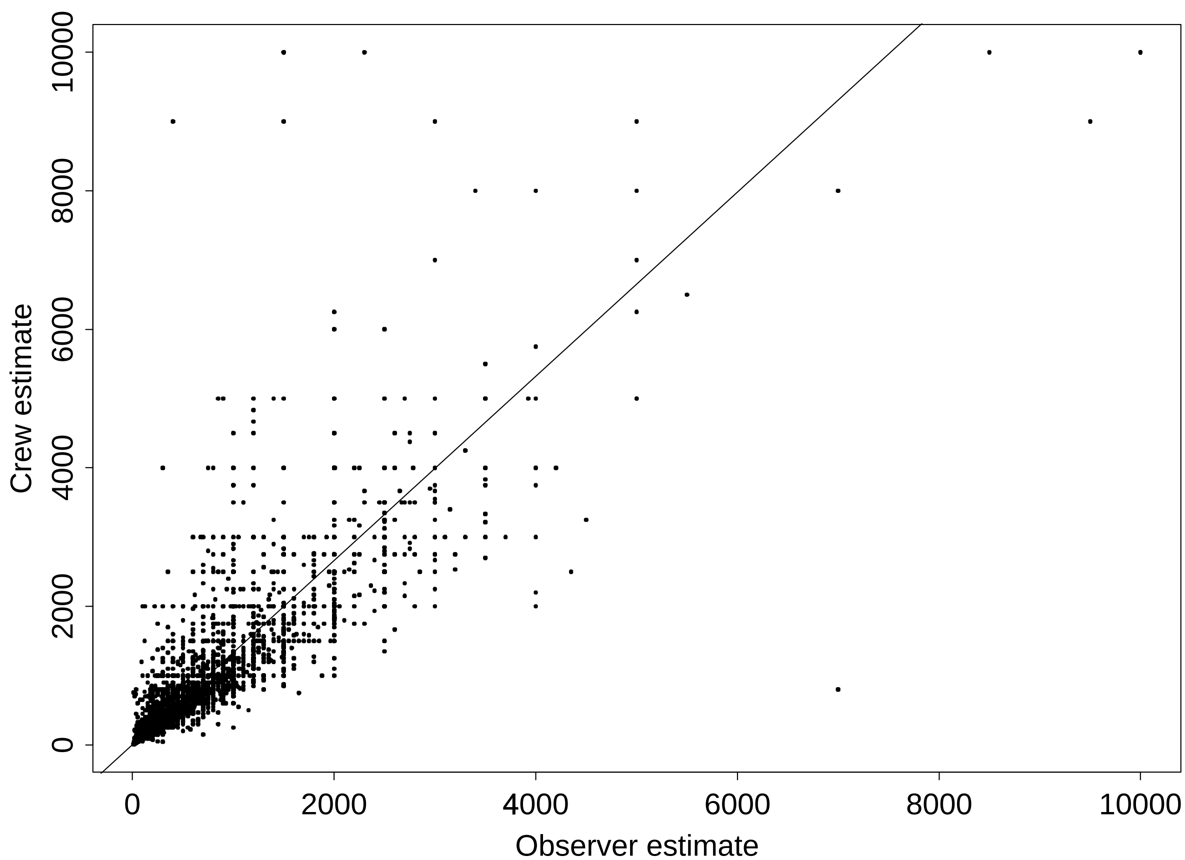

Figure 8. A cluster of eighteen sets made on northeastern offshore spotted dolphins by nine U.S.-flag tuna purse seiners in the ETP in 1987. These sets occurred over three days, in an area approximately 31nmi by 47nmi. The sets were observed by either NMFS- and IATTC-trained scientific observers. *s* is the observer's estimated total school size.

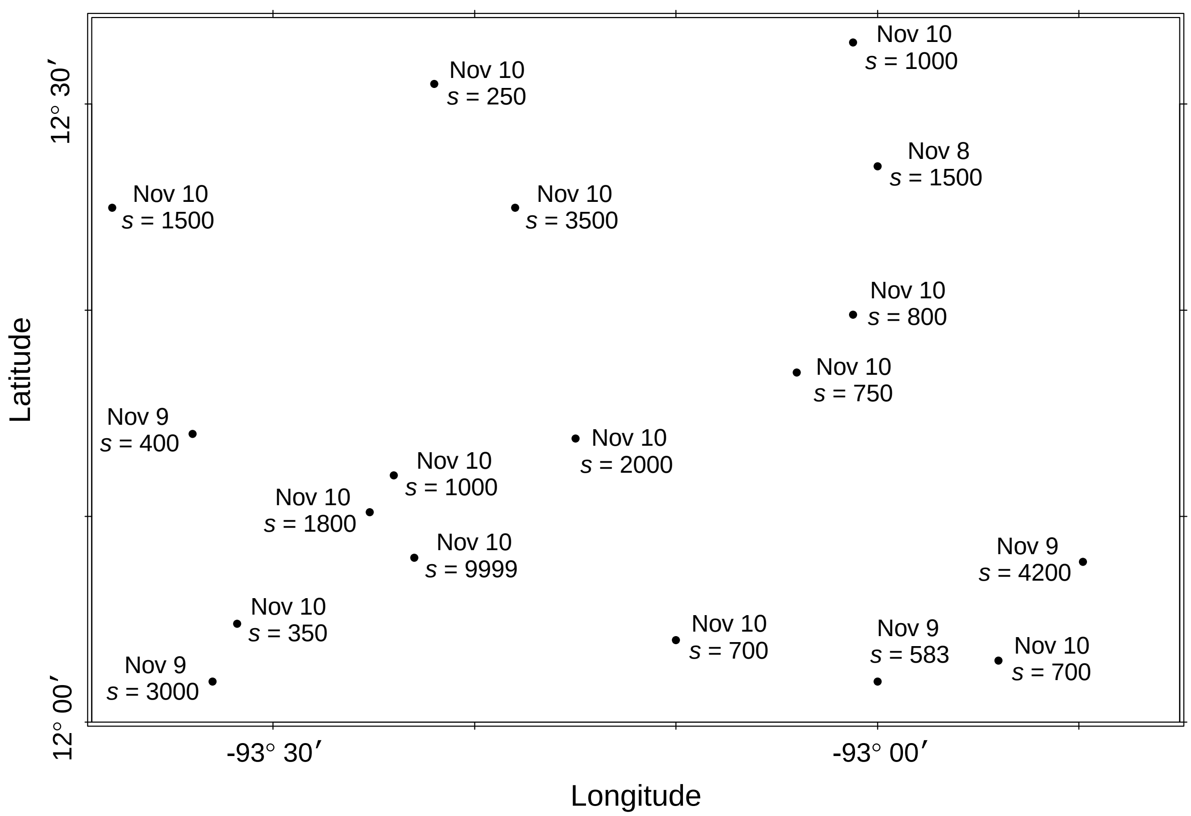

Figure 9. A sequence of five sets made on northeastern offshore spotted dolphins by a single U.S.-flag tuna purse seiner in the ETP in 1989. These five sets occurred consecutively over two days, in an area approximately 9nmi by 23nmi. The sets were observed by an IATTC-trained scientific observer. *s* is the observer's estimated total school size.